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ABSTRACT

A processing system has been developed to meet increasing demands for detailed noise measurement of aircraft in wind tunnels. Phased arrays enable spatial and amplitude measurements of acoustic sources, including low signal-to-noise sources not measurable by conventional measurement techniques. The Microphone Array Phased Processing System (MAPPS) provides processing and visualization of acoustic array measurements made in wind tunnels. The system uses networked parallel computers to provide noise maps at selected frequencies in a near real-time testing environment. The system has been successfully used in two subsonic, hard-walled wind tunnels, the NASA Ames 7- by 10-Foot Wind Tunnel and the NASA Ames 12-Foot Wind Tunnel. Low level airframe noise that can not be measured with traditional techniques was measured in both tests.

INTRODUCTION

Civil aircraft must meet noise certification standards set by the FAA [1] in the United States. Most countries follow the noise standards set by ICAO [2]. Several individual airports enforce their own stricter noise rules. Jet noise was the dominant source of noise produced by aircraft in the past. Since the 1950's, noise from jet engines has been reduced significantly so that airframe noise is now a significant contributor to the total noise from modern aircraft, especially in the landing configuration. In the wind tunnel, it is very difficult to measure airframe noise with traditional methods due to background noise, reflections and multiple sources. The phased array technique enables measurements of low noise sources in a high noise environment and the identification and localization of multiple acoustic sources. Low level noise from individual aircraft components such as landing gear, flaps and slats may be measured in a wind tunnel with the phased array technique. These measurements facilitate selection of lower noise components to meet noise certification standards early in a design. This requirement for detailed knowledge of acoustic sources in an environment with low signal-to-noise ratio led to the development and application of microphone array technology to wind tunnel testing. As part of a larger effort to develop phased array noise measurement systems at NASA Ames Research Center, this paper describes the developed of a system to process and visualize phased array noise measurements.

Early attempts by Soderman [3] and Brooks [4] to measure noise in wind tunnels with phased arrays met with limited success. More recently, several research groups have developed array systems for use in wind tunnels [5-14]. Most of the groups use and continue to develop their array systems. Improvements in computers, data systems and instrumentation enabled this development.

The system described in this paper is unique because it is an end-to-end system designed to be used by researchers who differ from the developers. Important factors contributing to the usability and usefulness of arrays in testing environments today include ease of use in processing and visualization interfaces, efficient handling of large quantities of data, quickly obtaining calibrated results, and displaying results in an understandable manner. The use of point and click interfaces provides intuitiveness and ease of use in modern systems. This is a desirable goal as it reduces training time and thus increases the number of users of the system. The combination of large numbers of microphones and the desire to process a large number of frequencies results in the production of large files for each test point. Thus, the network transfer of, and disk access to, data files become issues when considering the bottlenecks in system throughput.

Traditional piston phone calibration techniques do not take into account installation or directionality effects. Additionally, the individual calibration of large numbers of microphones is time consuming and tedious. Thus the calibration of array microphones is an important aspect in designing an array system able to produce calibrated results in a timely manner. Array systems not only produce large quantities of raw digital data, but large quantities of processed data. The ability to view and assimilate this data efficiently is as important as producing the results. After all, if the data is acquired but never used then all the time and money spent in development and testing is wasted.

The requirements mentioned above led to the development of the Phased Microphone Array Technology (PMAT) system. The PMAT comprises two parts: 1) instrumentation and data digitization and 2) data processing and visualization. The Microphone Array Phased Processing System (MAPPS) comprises the second part of PMAT. MAPPS has been successfully used in tests at NASA Ames Research Center [15,16]. This paper will discuss the implementation of these requirements into MAPPS.

SYSTEM DESCRIPTION

MAPPS was developed as part of the Phased Microphone Array Technology (PMAT) system that encompassed signal measurement, analog to digital conversion, data storage, data processing and results visualization. MAPPS begins at the end of the data acquisition and storage and ends with the processed data visualization. This system is designed to be versatile and robust in its treatment of variable numbers of microphones, number and locations of processors, versatile calibrations, and visualization requirements. This versatility is designed into the system to provide for alternatives if components fail. These component failures will result in degraded results, but the results will still provide the researcher with information to meet their needs. Ease of use of the system was also a cornerstone of the design constraints. A point and click graphical interface to the processing and visualization codes was thus developed. This point and click environment will allow a minimally trained researcher to operate the system. The system is designed so that the user may concentrate on research, testing and data interpretation, instead of data and file manipulation.

An operational design goal for MAPPS was to provide sufficient results in near real time to allow the test director and researcher to make future run content decisions. The first operational test of MAPPS was in a recent Flap Edge test using a 100-element microphone array in the NASA Ames 7-by 10-Foot Wind Tunnel [15]. The system had a 9-minute cycle from end of data acquisition to showing results on screen for 166 frequencies with 400 averages and a frequency resolution of 150 Hz. This cycle time was sufficient to obtain results from a small number of points for each run condition and to allow the test director to make model change and run condition decisions for the next run. Another operational design consideration was to have all the data processed and ready for examination by the next day. The ability to batch process multiple data points was also demonstrated at this test.

The MAPPS system starts with a raw time history and produces a processed data file and computer visualization of the results. The input raw data file and the output processed data file are both stored in a widely used self describing, machine independent binary file format called Network Common Data Format (netCDF) [17]. Besides the basic data, these data files contain all the information related to the instrumentation, test setup and test conditions. MAPPS includes many files and computer programs (Figure 1). The user sets all the processing parameters and initiates interactive processing through the Process Control Interface. The Processing Control interface reads the header information in the Raw Time History Data File. Processing parameters may be used from a file or set interactively based upon information derived from the header and displayed in the Interface. All the processing parameters are saved in the Process Settings File. The data processing occurs in four processes that run without user interaction once the Control Process is started by the Processing Control Interface or a UNIX script for batch processing. The computer running the Control Process must have access to the Processing Settings File that was written by the Processing Control Interface. The Read Data Process must have access to the Calibration File(s) and the Raw Time History Data File. When processing is complete, the Output Process writes the results and header to the Processed Data File. The header of the Processed Data File contains all the information from the header of the Raw Time History Data File plus all of the parameters used to process the data. Data visualizing is done in a separate process. Visualization requires access to the Processed Data File and Model Projection File.

PROCESSING ARRAY MEASUREMENTS – In phased array processing, signals from several transducers are combined to produce an image of noise sources over a selected region of space. For each location in the scanned region, signals are combined so that they add coherently for sources at that location and incoherently for other sources and noise. Johnson and Dudgeon [18] provide a basic description of phased array processing. The processing in MAPPS differs from the standard array processing in order to account for differences in the wind tunnel environment. The signal processing is based upon radiating point sources in a uniformly convecting flow instead of plane waves in a quiescent medium. If convection is ignored, the correct location will not be identified. If the plane wave assumption were used, the amplitude would be wrong by several dB in a typical wind tunnel application. Processing can be done on an arbitrary arrangement of microphones in the array, instead of just a uniform array. With non-redundant spacing in the array, good results can be produced for the wide frequency range applicable to the measurement of aircraft noise. More details on the basic processing techniques are contained in Mosher [19].

Options to process the data are selected in a graphical user interface. For ease in processing, options may be saved for reuse in a user named setup file. Watts [20] describes the processing options and how to use them. The main control interface (Figure 2) contains information about the data, provides for setting processing options and provides access to more windows for detailed information and option settings. The program can handle data that has been segmented into disjoint groups to allow statistical sampling of data over a long period without saving the unused data between groups. Each block of data comes from a single group. The user can select blocks of data and groups of blocks of data to be processed. The block size is variable, within the constraints that the block size is of the form $2^l 3^m 5^n$ with integer values of l, m and n, and within the amount of data available in a group. These features provide great flexibility in selecting the frequency resolution and quantity of data to be processed. Time-domain windowing may be selected from rectangular, Hamming, Hanning or Blackman. Locations for processing may be specified on a grid or from a PLOT3D [21] formatted geometry file. Processing may be done assuming spherical waves or plane waves. The effects of uniform flow may be included or not. An incoherent noise reduction scheme may be included to reduce the interference from background noise. Signal gains from the data file or user input may be used. A subset of microphones from the array may be chosen through another window (Figure 3). The processing also checks for bad data, and eliminates the bad data from the processing. If the processing program determines that the quantity of deleted data is large enough to significantly alter results, a message will be included with the output.

A complete calibration of an array involves phase and amplitude calibrations including the installation mounting effects on the acoustic field. In order to accurately locate noise sources, the *in situ* phase response of all microphones in the array must be known; however, the amplitude can be unknown as long as all microphones have similar sensitivity. Accurate source level measurements require accurate array amplitude as well as phase calibrations. The standard piston phone procedure is time consuming for large numbers of microphones and fails to account for the installation or directional sensitivity effects on the acoustic measurements. MAPPS offers two methods of calibration, one labeled “Ames” developed by the authors of this paper and the other “Boeing 95” developed by Dougherty and Underbrink [6,7]. The Ames method provides separate operations to calibrate sensitivity, individual channel amplitude and phase as a function of frequency and atmospheric pressure, installation effects and free field effects prior to the scan operation. The Ames method provides separate options for directivity correction and density correction after the scan operation. All of these calibration options are controlled through a control calibration interface window that is accessed through the main control window. Calibration files are needed to run the Ames method. Watts [20] contains a description of all the necessary files and the calibration procedures to generate the information in the files. MAPPS includes several separate processes written in MATLAB® to produce the calibration files from the appropriate data. The “Boeing 95” method is for data collected with the Boeing system.

MAPPS processing software was designed to process large acoustic data sets in near-real time to provide the location and amplitude of acoustic sources. It contains four programs (Figure 1) executing multiple processes allocated in machines with single and/or multiple CPUs. It has the capability to run in a single workstation or a heterogeneous network of computers. A brief description of the main activities of each program is described here. The Control program defines all the processing, machine allocations, and starts the Input and Parallel Processing programs from a workstation with the required network privileges to access all other machines using the Parallel Virtual Machine (PVM) library [22]. The Input program dynamically allocates the memory, reads all the acoustic data and calibration files and sends them to the leader Parallel processor. The Parallel Processor program executes the processing subdivided in parallel tasks with one of these tasks acting as the lead processor. The subdivision of tasks is based on blocks of acoustic raw data before data averaging and based on groups of processing frequencies in the scanning process. Use of larger subdivisions or numbers of parallel processes decreases the execution times of particular tasks; however, use of more processors increases the time spent on transferring information between the parallel tasks. The Output Program is started by the lead Parallel Processor once all the scanning is complete and it receives the location and amplitude of the acoustic sources from the lead processor. The information is stored in the corresponding files.

The following table shows the performance of the program processing 101 microphones, 315 frequencies and 18894 scanning points. The Parallel Program was executed in a single CPU Silicon Graphics Power Indigo^2 workstation and compared against processing in two parallel computers of the Numerical Aerospace Simulation (NAS) facility at NASA Ames Research center, the Origin 2000 cluster and DaVinci cluster. DaVinci was a NAS designation of an SGI Power Challenge cluster each node consisting of a R8000 MIPS processor and 2 GB memory.

Table 1. Processing Time (minutes)

Number of CPU’s	DaVinci	Origin 2000 Cluster	SGI Power Indigo^2
1	-	-	49.65
2	50.88	22.87	-
4	26.25	12.33	-
8	23.63	8.37	-
16	23.83	7.43	-

A task was allocated in each CPU. The phased array scanning used about 80% of the processing time. As was expected, the total processing time decreases with the number of CPU's, however the increasing transfer of information between the parallel processes decreases the efficiency. Thus, the total efficiency is machine dependent. The net improvement from 49.65 CPU minutes in a single SGI workstation to 8.37 minutes when using the Origin 2000 cluster with 8 CPU's represents a significant reduction of over 83% in processing time.

Although processing time of about 8 minutes is too slow to keep up with data collection, it is fast enough to process a few data points while testing. This ability to analyze selected data points while testing is valuable because testing or data problems can be rapidly identified and addressed, thus increasing the quantity and quality of data that can be acquired during limited testing time. In a typical test, several hours are needed to process all of the data from one wind tunnel run. The availability of test results soon after testing enables a researcher to make judgements concerning the best use of available wind tunnel testing time.

VISUALIZING PROCESSED ARRAY MEASUREMENTS – Efficient and versatile visualization of array results is an essential part of MAPPS. Display of array results presents a complex problem for the system developer. Many instrumentation systems produce easily understood two- or three-dimensional data sets; however, array processing creates five dimensional data sets containing the physical x, y and z scan geometry as well frequency and amplitude. The size and complexity of the results puts a larger burden on the visualization software than in the past where the majority of effort was placed on the data reduction. MVIEW is a data visualization program written at Ames Research Center to view data processed with MAPPS. MVIEW was written in a fourth generation language known as PV-WAVE CL from Visual Numerics (http://www.vni.com). Scan results can also be loaded into the DARWIN [23] system. This system allows searching of the database for desired test conditions and performing preliminary looks at the array results. Researchers can then use MVIEW to investigate the desired test conditions in more detail.

Several types of data can be viewed in MVIEW. An overview plot contains three curves (Figure 4). The three curves show the average level of all the good microphones, the maximum level found in the scan and the average level found in the scan as functions of frequency. This plot of curves assists the user in determining which frequency data to view in detail. Other plot windows displaying the scanned data are started through the MVIEW overview window. Figure 5 shows an example of a 2-dimensional plot. White dots identify the grid of the model. The scanned sources are displayed as colored maps and/or contours. The user can control the scale on the map. The two-dimensional plot displays array results for one frequency. This plot can also be animated to display results for successive frequencies to run like a movie by clicking on the start animation button in the overview plot window.

For distributed sources, the maximum scan value is not an accurate indication of the radiated acoustic level. Dougherty [6] suggested a method to evaluate the effect of multiple or distributed sources within an area from the array response map. A region is defined in the scan area. The integral of the array response over that region is computed and referenced to the integral over the same region of the array response to an ideal point source. This new metric relates the source strength to the integral of the array response instead of the maximum of the array response. Source integration is implemented inside MVIEW. A polygon source integration region may be specified graphically or through a file. Figure 6 shows the results of source integration. The dropouts occur where there is no source identified in the selected integration region.

Images showing the health of the microphone signals in each block of data can be accessed through a pull-down menu. Figure 7 shows an example of the microphone health with most data identified as good. Data is identified as bad and excluded from processing if the microphone is declared bad, is band edged, has a flat spot, or if it differs from the average by more than a parameter specified by the user.

EXAMPLE

Data (Figures. 4-7) come from a test of a wing with a three-dimensional high-lift system in a hard-walled subsonic wind tunnel [15]. Background noises of the wind tunnel and flow noise over a microphone preclude measuring noise from the wing with conventional techniques. The average background noise measured by the array microphones falls in the range of 15 to 20 dB above the largest acoustic pressure measured at the scanned locations (Figure 4). The scan image visualization (Figure 5) includes the model and results of a phased array scan for one frequency. The wind tunnel flow is from left to right. The top view of the wing includes the leading edge slats and the half-span trailing edge flaps. In the scan image (Figure 5), the largest amplitude occurs near the flap edge; some other strong sources occur near the leading edge slats. Several small "sources" can be found throughout the scan in the range of 6 to 8 dB below the maximum. Some of these small sources are probably noise from the wing structures and some of these small sources are from the background noise. The flow induced noise sources found at the flap edge and slats persist across multiple frequencies. Background noise was obvious in the scans and occurred at different locations for different frequencies, making it obvious that the associated local maxima were not from significant sources. Since this example shows measurements are feasible in a hard-walled wind tunnel, it is clear that the system can be used for other purposes and in other environments such as looking for the louder machines in a room full of operating machines.

CONCLUSION

This paper describes MAPPS, a system for processing and visualizing phased array measurements made in a wind tunnel. The system is designed to meet the specific needs of testing in a closed test section wind tunnel. It has been used in wind tunnels at NASA Ames Research Center to produce noise measurements that can not be made with other technology. Noise from individual airframe components has been measured.

REFERENCES

1. Title 14 of the U.S. Code of Federal Regulations, FAR Part 36--Noise Standards: Aircraft Type and Airworthiness Certification, http://www.faa.gov/avr/AFS/FARS/far-36.txt.
2. Chapters 2 and 3 of Volume I of Annex 16 to the Convention on International Civil Aviation.
3. Soderman, P. T. and Noble, S. C., "A Directional Microphone Array for Acoustic Studies of Wind Tunnel Models," AIAA Paper 74-640, AIAA Aerodynamic Testing Conference, 8th, Bethesda, Md., July 8-10, 1974.
4. Brooks, T. F., Marcolini, M. A. and Pope, D. S., "A Directional Array Approach for the Measurement of Rotor Noise Source Distributions with Controlled Spatial Resolution," Journal of Sound and Vibration, vol. 112, Jan. 8, 1987, p. 192-197.
5. Elias, G., "Noise Source Localization with Focussed Antenna for Reduction Purposes," Presented at the Science et Defence Conference, France, 15-16 May 1990, p 1-13 Transl. into ENGLISH from Science et Defence (France), 15-16 May 1990, p 1-13.
6. Dougherty, R. P. and Underbrink, J. R., personal communication, The Boeing Co., Dec. 1994 to 1998.
7. Dougherty, R. P. “Phased Array Beamforming for Aeroacoustics” AIAA Professional Development Short Course, Bellevue, WA, May 8-9, 1999.
8. Dine, C., Gely, D. and Elias, G., "Supercritic and Subcritic Jets Acoustic Imaging Study" 2nd French Acoustic Congress, Arcachon, France, April 14-17, 1992.
9. Gramann, R. A. and Mocio, J. W., "Aeroacoustic Measurements in Wind Tunnels using Adaptive Beamforming Methods," Journal: Journal of the Acoustical Society of America vol. 97, no. 6 p.3694-701, June 1995.
10. Watts, M. E., Mosher. M. and Barnes, M., "The Microphone Array Phased Processing System (MAPPS)," AIAA 96-1714, 2nd AIAA/CES Aeroacoustics Conference, State College, PA, May 6-8, 1996.
11. Meadows, K. R, Brooks, T. F., Humphreys, W. M. Hunter, W. H. and Gerhold, C. H., "Acoustic Measurements of a Wing-Flap Configuration," AIAA 97-1595, 3rd AIAA/CES Aeroacoustics Conference, Atlanta, GA, May 12-14, 1997.
12. Humphreys, W. M, Brooks, T. F, Hunter, W. M. and Meadows, K. R., "Design and Use of Microphone Directional Arrays for Aeroacoustic Measurements," AIAA 98-0471, 36th Aerospace Sciences Meeting & Exhibit, Reno NV, January 12-15 1998.
13. Brooks, T. F and Humphreys, W. M, "Effect of Directional Array size on the Measurement of Airframe Noise Components," AIAA 99-1958, 5th AIAA/CES Aeroacoustics Conference, Bellevue, WA, May 10-12, 1999.
14. Sijtsma, P. and Holthusen, H, "Source Location by Phased Array Measurements in Closed Wind Tunnel Test Sections," AIAA 99-1814, 5th AIAA/CES Aeroacoustics Conference, Bellevue, WA, May 10-12, 1999.
15. Storms, B. L., Hayes, J. A. Morairy, P. J. and Ross, J. C., “Aeroacoustic measurements of Slat Noise on a Three-Dimensional High-Lift System,” AIAA 99-1957, 5th AIAA/CEAS Aeroacoustics Conference, Seattle, WA, May 10-12, 1999.
16. Hayes, J. A., Horne, W. C., Jaeger, S. M. and Sodernan, P. T., “Measurement of Reynolds Number Effect on Airframe Noise in the 12-Foot Pressure Wind Tunnel,” AIAA 99-1959, 5th AIAA/CEAS Aeroacoustics Conference, Seattle, WA, May 10-12, 1999.
17. Rew R., Davis, G., Emmerson, S. and Davies, H., ”NetCDF User’s Guide for C”, University Corporation for Atmospheric Research http://www.unidata.ucar.edu/packages/netcdf/guidec/ , June 1997.
18. Johnson, D. H. and Dudgeon, D. E., “Array Signal Processing: Concepts and Techniques,” Prentice-Hall Inc., 1993
19. Mosher, M., “Phased Arrays for Aeroacoustic Testing: Theoretical Development.” AIAA96-1713, 2nd AIAA/CEAS Aeroacoustics Conference, State College, PA, May 6-8, 1996.
20. Watts, M. E.; Mosher, M.; Barnes, M.; and Bardina, J., “Microphone Array Phased Processing System (MAPPS) Version 4.0 Manual,” NASA TM March 1999.
21. Walatka, P. A, Clucas, J., McCabe, R. K., Plessel, T. and Potter, R. “FAST Users Guide” NASA Ames Research Center: NAS Division, RND Branch, RND-93-010 January 1994.
22. Geist, A., Beguelin, A., Dongarra, J., Jiang, W., Manchek, R., Sunderam, V., “PVM 3 User's Guide and Reference Manual,” Engineering Physics and Mathematics Division, Mathematical Sciences Section, Prepared by the Oak Ridge National laboratory, Oak Ridge, Tennessee 37831, ORNL/TM-12187, May 1994.
23. Korsmeyer, D. and Walton, J. D. "DARWIN v2 - A Distributed Analytical System for Aeronautical Tests," AIAA-98-2719, 20th AIAA Advanced Measurement and Ground Testing Technology Conference, Albuquerque, NM, June 1998.

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APPENDIX

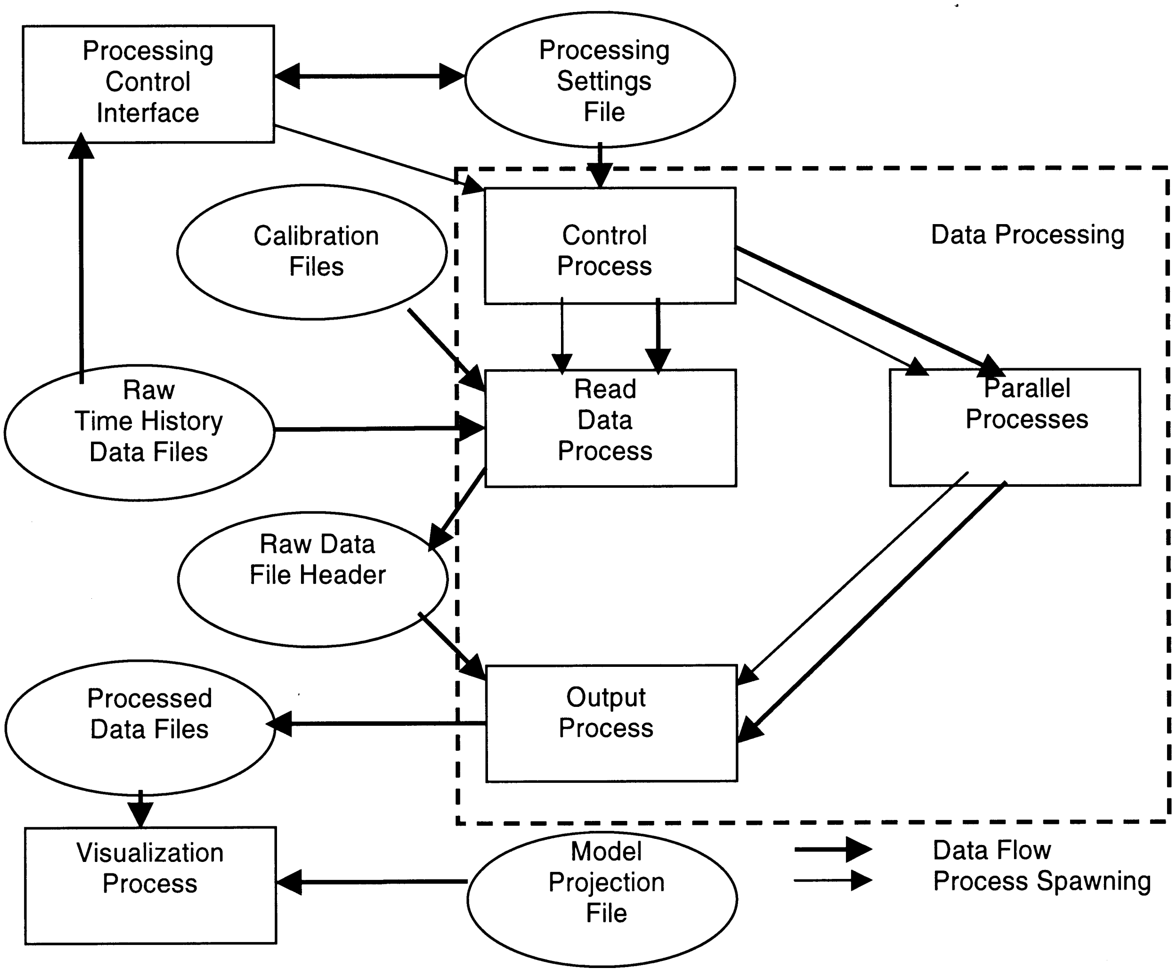

Figure 1. Overview of MAPP

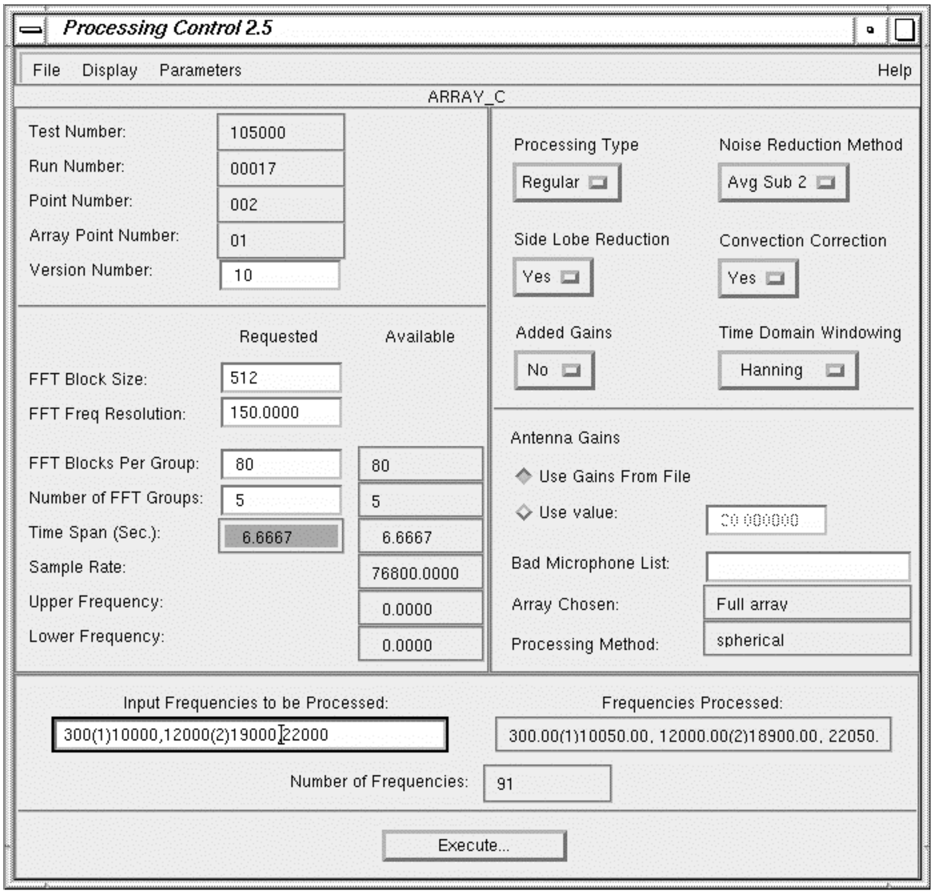

Figure 2. Processing Control Interface Main Window

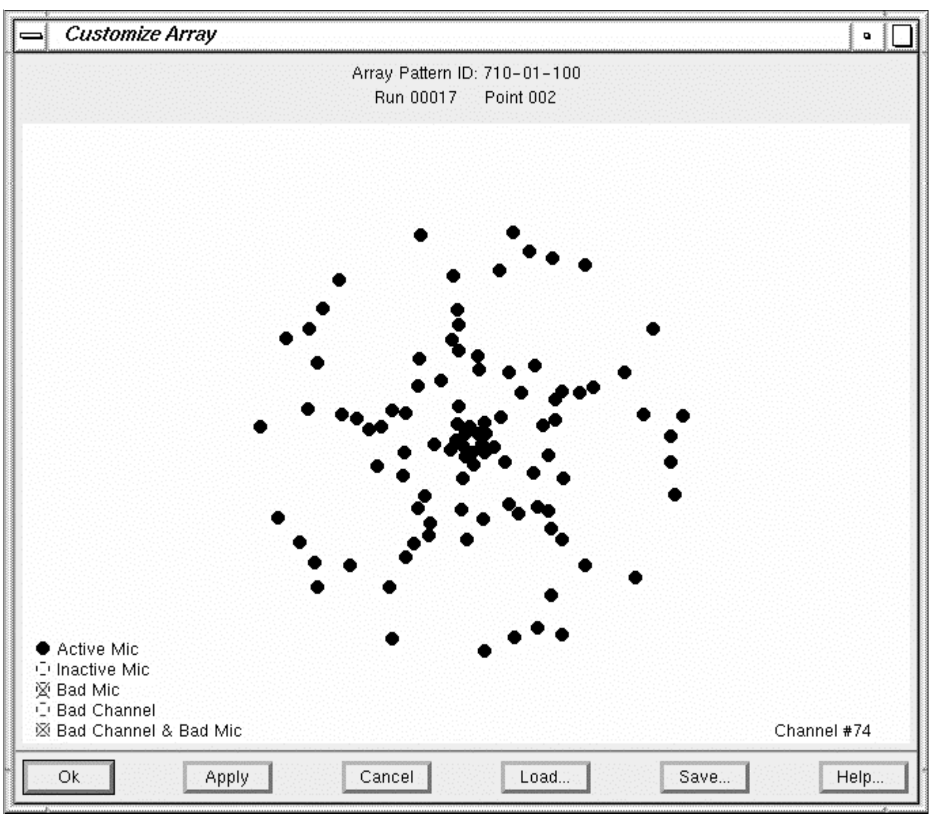

Figure 3. Processing Control Interface Array Customization Window

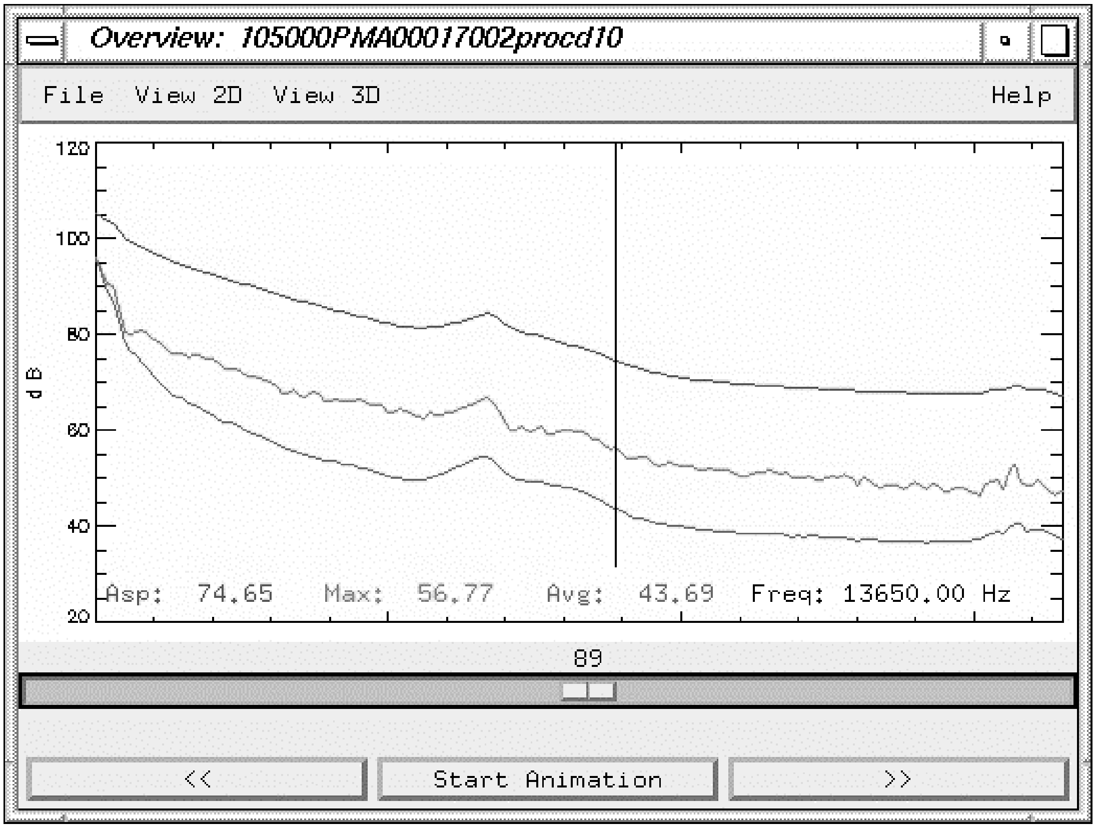

Figure 4. MVIEW Line Plots of Data

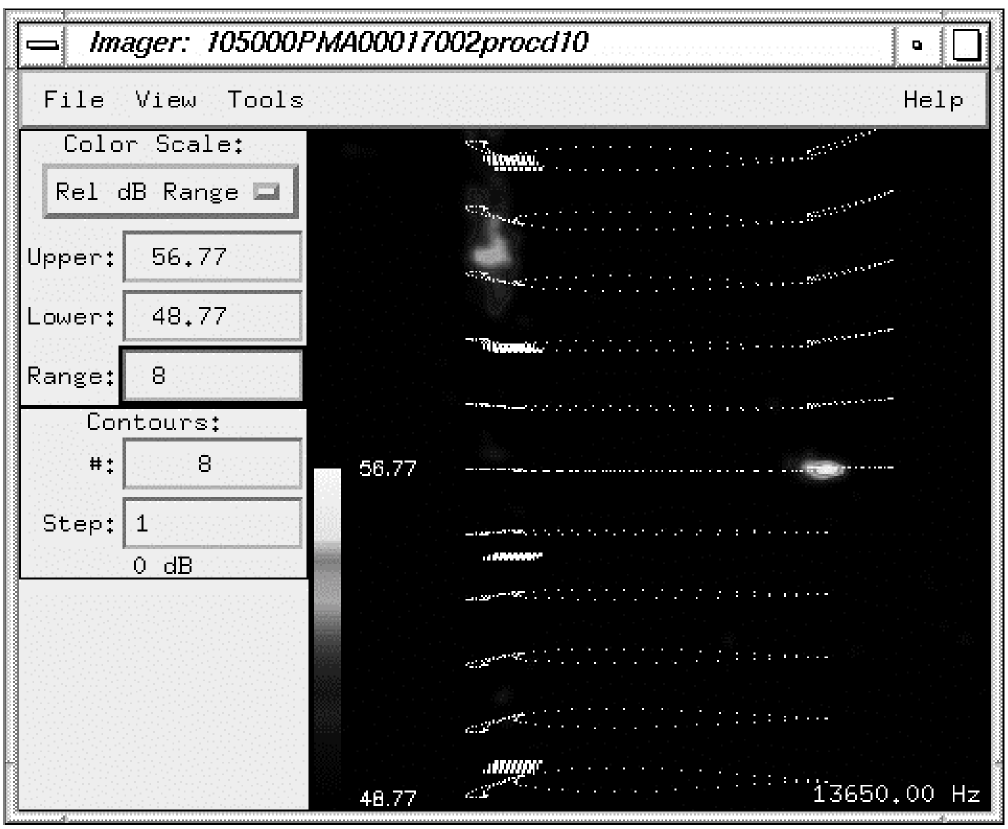

Figure 5. MVIEW Imager Window

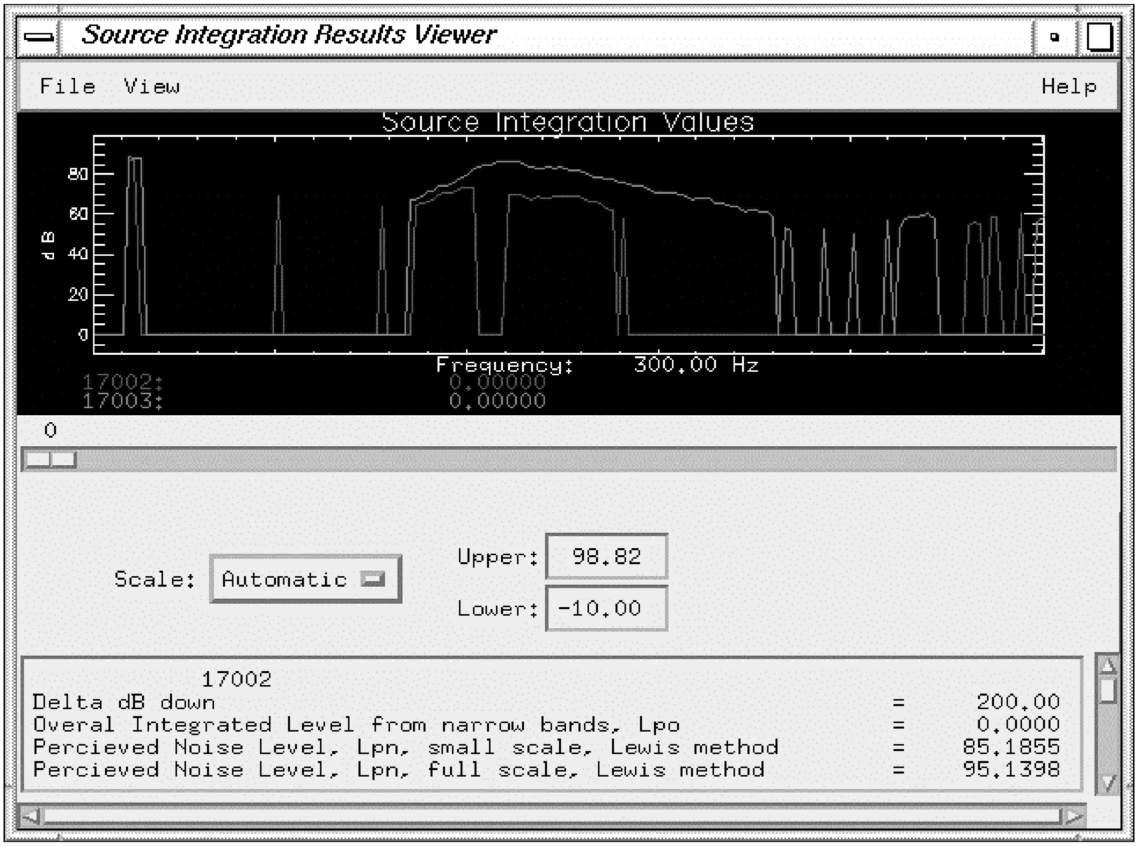

Figure 6. MVIEW Source Integration Window

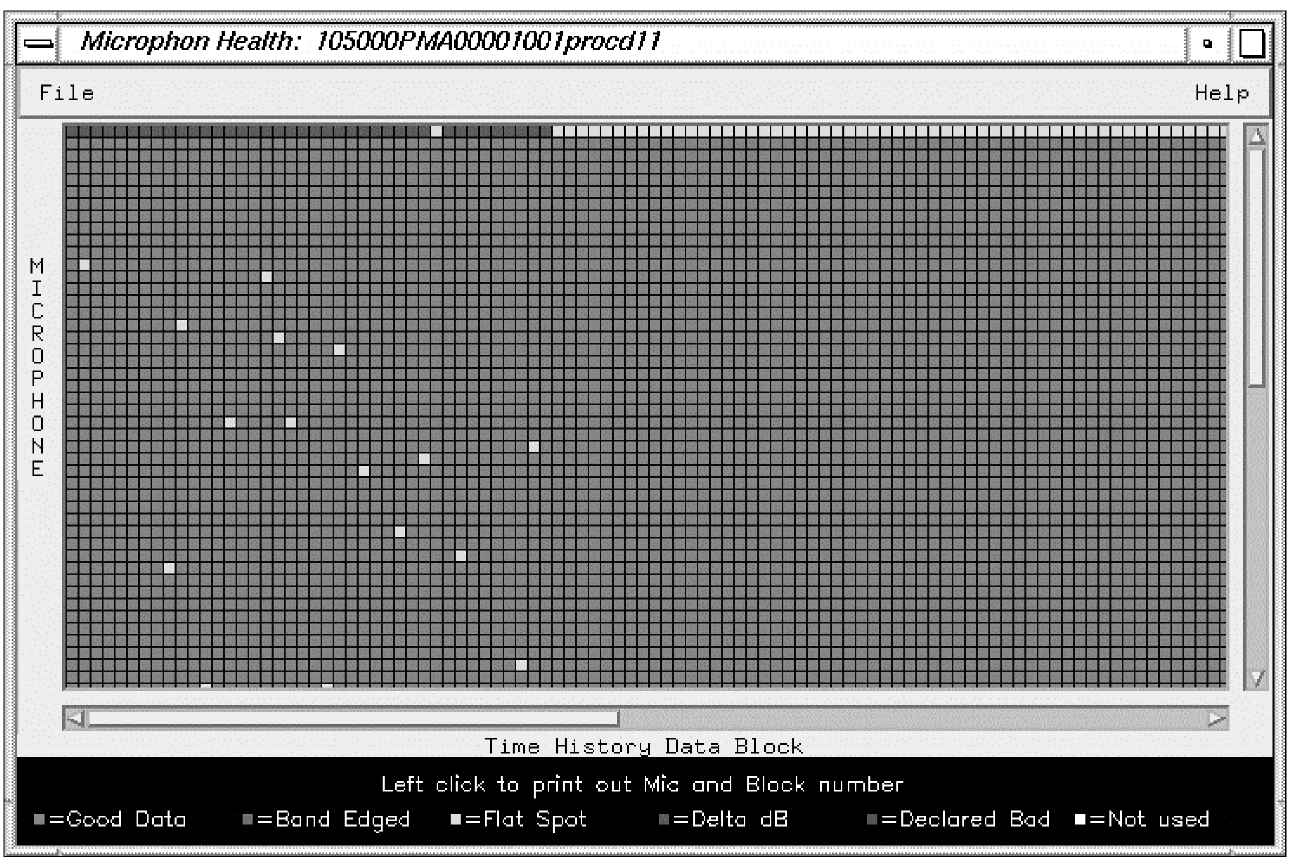

Figure 7. MVIEW Microphone Health Window